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## Lifecycle Analysis: Uses and Pitfalls

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### Introduction

Lifecycle analysis (LCA) is a powerful tool, often used as an aid to decision making in industry and for public policy. LCA forms the foundation of the newly-invented field of industrial ecology. There are several possible uses and users for this tool. It can be used to evaluate the impacts from a process or from production and use of a product. Impacts from competing products or processes can be compared to help manufacturers or consumers choose among options, including foregoing the service the product or process would have provided because the impacts are too great. Information about impacts can be used by governments to set regulations, taxes, or tariffs; to allocate funds for research and development (R&D) or low-interest loans; or to identify projects worthy to receive tax credits. In addition, LCA can identify key process steps and, most important, key areas where process changes, perhaps enabled by R&D, could significantly reduce impacts. Analysts can use the results to help characterize the ramifications of possible policy options or technological changes.

The basic procedure is, in concept, relatively straightforward. Examine the entire system, evaluate the impacts, and choose the best option. But in actual practice, there are a number of difficulties. Each of the key words used in describing the procedure needs careful definition, or the results obtained may be different. The system must be defined so that the entire lifecycle is included, or important effects may be neglected. Alternatively, smaller systems with equivalent inputs and outputs can be compared. The impacts of concern must be identified, and these can range from the effects of a single air emission (e.g., CO<sub>2</sub>) to total financial costs. Impacts may be difficult to evaluate, and they may be regional or global, as well as distributed in time. The analyst or decision-maker must finally decide what is meant by "best." If there are trade-offs among impacts, how should they be weighted? Different weightings might imply different decisions.

The procedures for performing the inventory part of a lifecycle analysis, where the measurable inputs and outputs from the system are determined, have been very well defined by such groups as the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organization for Standardization (ISO). Adherence to the standard methodology makes it easier for anyone to do such an analysis. That is both good and bad. It eliminates certain common types of errors and assures at least minimal consistency among studies. But it also imparts credibility to anyone adhering to the standard procedure, while still leaving several potential pitfalls that even reputable and experienced analysts can fall into. The next stage of the analysis, where the health and environmental impacts of the inventory items are evaluated, has not been standardized because of the many difficulties involved.

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This paper describes our interpretation of LCA concepts, including some areas where we differ with the current standard procedures. It also provides examples (from LCAs related to municipal solid waste [MSW] management) of pitfalls and illustrates ways to avoid them.

## **LCA Concepts**

This section briefly describes our concept of LCA. LCA is an effective tool when a decision must be made about how to deal with a specific, limited problem. (For some purposes, larger problems can be tackled, but these and the associated institutional issues are very complicated.) The logical steps in the LCA procedure are described below. We note where the standard procedure can be broadened conceptually or modified to provide more meaningful results.

**System Definition** — The first step in a complete LCA is to determine what consumers actually require. They do not usually require a specific product made from a specific material, but rather a service that will meet their primary needs (such as freshness of the contents of a package). Once the actual requirements are identified, the next step is to define all of the acceptable means to satisfy them (such as using a different process to produce the product or recycling it). In a real analysis, a smaller set of options (e.g., paper and plastic grocery bags) is usually chosen because of limited time or money available for the work. All of the inputs and outputs associated with each option must be identified; care must be taken to ensure that systems to be compared have equivalent functionality. For instance, if one produces a co-product, appropriate credits must be given.

**Lifecycle Inventory** — The next step in the analysis is to actually perform an inventory of all of the inputs and outputs for every element of the system and for each process or product option. The items in the standard inventory are generally energy and materials, including effluents, but lifecycle costs can also be determined. Energy may be tabulated by type or aggregated; we believe it is important to account for different energy types separately because of concerns about fossil fuel use and greenhouse gas emissions. In addition, we differ from the standard methodology by accounting for all of the energy content in the wood input to paper and pulp manufacture. This is necessary if lifecycles including combustion are to be evaluated properly.

Two alternative methods can be used to determine the lifecycle inventory: input/output (I/O) analysis and process analysis. Each has advantages and disadvantages, but we prefer to use process analysis because newer and more detailed data are generally available and the effects of technological changes are more apparent. On the other hand, I/O captures all the effects from a process throughout the entire economy. Since most I/O tables for the U.S. economy are in dollars, this is most useful for a financial LCA. Process analysis is the method generally used in standard energy and environmental LCA. The collection and interpretation of data for process analysis are nontrivial activities and the subject of a considerable volume of literature. If time is limited, it is important to focus attention on those processes that make significant contributions to the total inventory or differ among options. A quick scoping analysis is therefore a useful first step that can precede the standard analysis.

We employed flowcharts to aid in our understanding of energy and material flows in industrial processes (inputs and outputs, including residuals). An example is provided in Figure 1. It is important to allocate inventory items among co-products correctly. (The generally-used convention of allocation on a weight

basis may not always be appropriate; an obvious example is petroleum refinery products, where the impacts from the extra processes required to enhance gasoline yields should be charged to that product alone.) Care must also be taken to distinguish between data based on all production facilities (average) and those from new (marginal) capacity, because the latter are often more relevant for decisions about future production. One recent study failed to recognize this fact and suggested policy based on industrial process emissions averaged over 50 years, including a period prior to United States Environmental Protection Agency (USEPA) regulation. It is also important for some analyses to retain information about geographical and temporal distributions of the inventory items. This is compatible with but not included in the standard procedure.

Once the data are assembled, the inventory items are added up to provide a total profile for each option. In many LCAs, the inventory is the final product. However, even though it is very difficult to do an impact analysis (the next step in the standard SETAC methodology), the inventory can provide useful information to aid decision makers. No guidelines exist for interpretation and use of inventory data.

**Criteria Choice** — The analyst or decision-maker must determine the goals to be accomplished (i.e., define the criteria to be used for choosing the best option). This is not generally part of a standard LCA. The choice of criteria is a policy decision; the criteria should be meaningful and explicit, rather than vague “motherhood and apple pie” justifications like conserving resources. Which resources do we want to conserve? Possibilities include energy in general, fossil fuels, trees, landfill space, and clean air. Other possible goals include minimizing costs, either for production or over the product’s life cycle. But any decision (including changes in lifestyle that would reduce or eliminate the demand) involves trade-offs. It is often difficult to conserve one resource without using more of another. So priorities must be more detailed, and may differ, depending on who is setting the policy and where the decision is being made. The inventory provides information on energy use and environmental residuals, but it does not rate their relative importance or evaluate impacts. Most discussions of impact analysis focus on the difficult task of evaluating health effects or environmental impacts of specific process effluents.

We considered what ideal criteria might be for making decisions, based at least partly on information gathered in the inventory analysis. Minimizing the total cost to society might be considered the ultimate criterion for a product or process choice. We attempted to analyze total costs in an early work on power generation options.<sup>(1)</sup> The total social cost includes the direct financial cost and indirect costs. Indirect costs, which differ for virgin and recycled products, are generally not reflected in the market price of the products. Indirect costs can result from impacts on unpriced resources (such externalities as air and water quality, wilderness, parks, and wildlife habitats), as well as costs to other parties (such as damage to buildings from acid rain). External costs are sometimes internalized by the government through regulations, such as limits on SO<sub>2</sub> emissions from utilities and industrial boilers. Other social costs that may not be adequately reflected in the market price are the time-related or strategic values of resources. For example, the current market price of petroleum may not reflect potential future economic scarcity, and the price does not reflect military operations to protect our supplies.

Full-cost accounting is a tool that attempts to assign values to all of the costs to society, but it is very difficult to implement properly. Most practitioners use it only for easily quantifiable financial costs. An ideal procedure would begin with all of the lifecycle process inventories and then estimate their impacts

(e.g., health and environmental), including long-term effects. Such an estimate is extremely difficult to make and has never actually been done. The next, even more difficult step, would be to quantify the relative costs (in terms of a single parameter like dollars) of the different impacts. Not only would this require a complex comparison (for example, a comparison of the costs to society from acid rain damage to forests in one region with the health effects from lead inhalation in another region), but it would also require a determination of the appropriate discount rates for future costs. The decision-maker would need to decide whether a human life in twenty years was worth less than one today. These are extremely thorny issues, and societal consensus is unlikely. Therefore, this decision criterion, although perhaps ideal conceptually, is impractical to implement.

Since all of the societal costs are difficult to capture in an analysis, real decision makers use simpler criteria, such as minimizing petroleum usage or greenhouse gas emissions, that are easier to evaluate because they result directly from the inventory. The options can be evaluated in terms of the chosen decision criteria. The standard analysis often ends here. In more complete analyses, the trade-offs are then identified and the implications for policy clarified. The preferred option best optimizes decision criteria; therefore, criteria should be carefully defined and meaningful because they will determine the decision. Results may also differ depending on the location being studied. For example, a decision to burn waste paper for energy recovery would be more appropriate in the U.S., where trees can be easily replanted, than in Switzerland, where trees are harvested from steep slopes.

There is no standard procedure for interpreting results. Many studies we reviewed failed to draw appropriate conclusions from the information gathered, even if the data were collected and presented in a competent manner. The studies we discuss are intended as examples only.

## Examples

The LCA examples presented below are both studies of alternative disposition options for municipal solid waste. Both studies carefully adhered to the SETAC methodology and presented results that may not optimize the stated or implied decision criteria. In both cases, kraft paper is the key material where we differ with the authors. The studies illustrate such pitfalls as overly narrow criteria, over-reliance on high-powered computer models, tacit use of incorrect key assumptions, and misleading conclusions due to aggregation. Another author has illustrated how standard allocation procedures and reliance on average rather than marginal plant data can also lead to incorrect results for kraft paper. (2) Although the reports discussed are apparently competent, they have flaws that could lead to adoption of policies that do not optimize the chosen decision criteria, such as those discouraging combustion of kraft paper. We identify shortcomings in these analyses and then suggest ways to improve them.

**CO<sub>2</sub> Emissions from MSW Treatment Options** — A major report, still in the draft stage, prepared for the USEPA (3) focuses entirely on CO<sub>2</sub> emissions from municipal solid waste management. This criterion choice is probably too narrow for rational decision-making. Although LCA allows it, analysis of any single impact in isolation is likely to neglect trade-offs with other important effects. It's the old fat-lady-in-the-girdle problem: Push the problem away in one place and it'll just pop up somewhere else unless you address the whole system. A similar error was made in the early discussions of nuclear power, when opponents based their entire analysis on possible health effects from improbable accidents, but ignored

the constant problems of respiratory effects of SO<sub>2</sub> emissions from coal combustion and traffic deaths caused by trains delivering coal.

The results in an early draft of this report apparently hinged on the unstated assumption that trees are not replanted after they are harvested to make paper. On closer examination, however, it turns out that the number of standing trees (and therefore the carbon sequestered) is actually assumed to be held constant whether or not trees are harvested and is increased if paper was recycled. That is, the authors tacitly assume that *additional* trees are grown if paper is recycled. This assumption is probably not correct, and at a minimum, the authors need to discuss the impact of this assumption on their results. It directly biases the results for the only parameter of interest in favor of recycling and is therefore a key assumption. We suggest sensitivity analysis to key parameters; this has been done in several reports by Franklin Associates and others. The hidden assumption that additional trees are planted is related to the generally unclear and inconsistent treatment of carbon sequestration in the draft report. There is also no distinction made between chemically pulped and mechanically pulped papers, which have very different net CO<sub>2</sub> impacts when recycled because of the different fuel mixes used to make them (much of the energy to make kraft paper comes from biomass by-products). Therefore, these cases must be analyzed separately.

The inappropriate assumption is obscured in a chapter about detailed modeling of the future of the forest products industry and is difficult to extract. Although use of a high-powered computer model gives credibility to any study, detailed calculations using assumptions and data that are at best uncertain may not provide meaningful results. Similarly, much effort in the draft report is expended on details about negligible impacts from unimportant elements rather than on identification and clarification of key elements. This does not create errors, but it provides the opportunity to lose the forest in the trees. For example, transportation energy is examined for all options, even though it is quickly seen to be much smaller than the uncertainties in everything else. It would have been better to make an estimate for one case with long distances, as part of a scoping step, and then decide to neglect it because it was so insignificant.

Another major problem concerns the efficiency of waste combustion used in this report. Average data on waste combustion are used, but if capacity were to be added, it would be either more efficient waste-to-energy (WTE) plants or co-combustion with coal or wood, as is practiced in some paper mills. For example, the mean value for the energy content of mixed MSW in a WTE plant is reported as 5358 Btu/lb, and the combustion efficiency is reported as 471 kWh per ton of mixed MSW combusted (4), representing an average thermal efficiency of 13.6%. However, a viable pathway for paper and other high-heating-value waste — combustion with coal or in waste fiber boilers in paper mills — is ignored. If a conventional coal-fired boiler's thermal efficiency is 29% (electricity production, including transmission losses), a first-order approximation of the thermal efficiency of a similar waste-paper-fired boiler or a boiler co-firing waste paper and coal would be about the same. Therefore, CO<sub>2</sub> emissions from waste paper combustion are over-estimated by 113% compared to co-combustion with coal. This error illustrates the problem caused by characterizing average rather than marginal technology. Alternatively, it illustrates the importance of identifying key parameters and estimating the sensitivity of results to them.

**Recycling of Solid Waste** — The second example is more subtle, because this generally competent and objective study for Keep America Beautiful (5) does not technically make any errors. However, the way

the data are presented supports a policy option that appears inconsistent with the presumed decision criteria. The study includes detailed appendices with careful estimates, using the SETAC methodology, of lifecycle inventories of energy and emissions for manufacture and recycling of each of the major components in municipal solid waste. Again, the material of interest is kraft paper, and an appendix includes the key fact that recycling of kraft paper may actually require *more* fossil fuel (but less total energy, if the energy content of the wood is included) than does production from trees. The conclusion based on this fact was highlighted in our work on MSW (6): if fossil fuel use (and CO<sub>2</sub> emissions) is to be minimized, perhaps kraft paper should be burned for energy rather than recycled, in order to conserve fossil fuel. However, this conclusion is not noted in the body of the example report. Instead, total energy use for all of the components in MSW is added up. The aggregation obscures important differences among materials.

The total energy use when MSW is recycled is correctly found to be lower than when all of the material is landfilled. "Overall, recovery for recycling saves energy... The most significant potential energy and environmental effects are realized when the recovered materials are utilized in place of virgin materials in the manufacturing process." (5) Therefore, maximum recycling is the option sought in both the main report text and in the executive summary, where only aggregated results are presented. The important information about paper recycling remains buried in the appendix. The more appropriate MSW strategy to conserve fossil fuel and minimize emissions, a mixed strategy including combustion of some components, could have been highlighted as beneficial.

The report also includes interesting information on costs; it would have been useful to explore the sensitivity of the results to these costs, which vary greatly with volatile waste paper prices. Scenarios with low waste paper prices, such as exist now, might have reduced the apparent desirability of paper recycling, while those with high prices would increase it.

## **Use of LCA in Decision Making**

A good LCA can conceptually aid in a variety of decisions, but the real world doesn't always work that way. In our free-market society, decisions are not made by a central planning organization that optimizes the total social costs or the criteria the society chooses for itself based on LCA, but on the basis of market prices of alternative products. These are, in turn, based only on the direct financial costs incurred by their producers, including the price of purchased resources used (materials, energy, labor), capital investments, profit taken, and any costs imposed by government action (these may be negative). Costs differ by location, both domestically and internationally.

The United States does not have a totally free-market economy; numerous government actions can change the direct costs to producers to either encourage or discourage the use of one product or process relative to another. Examples of such actions include subsidies, depletion allowances, targeted or low-interest loans, varying interest rates, research and development support, mandates, and regulations. Some of these actions, such as mandates for purchasing recycled products, may influence decisions regardless of cost. Producers and advocacy groups can also influence the public's perceptions of a product's true costs and benefits. Through selective education and advertising, they can change the public's preferences (changing the demand and, in turn, the price). Producers can also adjust the relative prices of the different products they sell. If the market does not naturally lead to the best solution



identified by LCA on the basis of selected criteria, the government, industry, and public interest groups can use any of these actions to influence the situation in favor of that solution.

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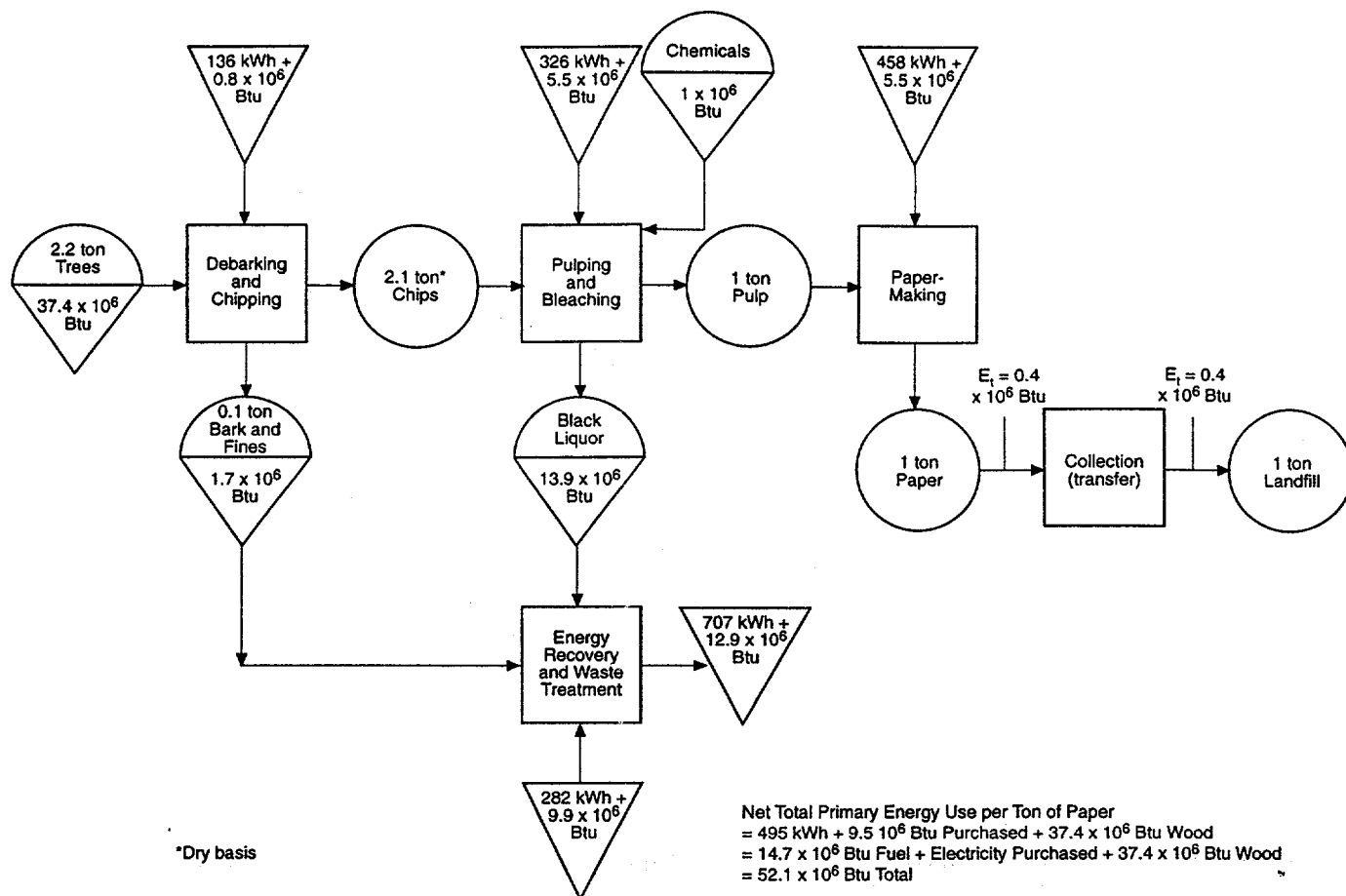


Figure 1. Energy and Materials Flow for Production of Kraft Paperboard